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A K-Band Linear Phased Array Antenna Based On $Ba_{0.60}Sr_{0.40}TiO_3$ Thin Film Phase Shifters

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A K-BAND LINEAR PHASED ARRAY ANTENNA BASED ON $Ba_{0.60}Sr_{0.40}TiO_3$ THIN FILM PHASE SHIFTERS

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ABSTRACT

This paper summarizes the development of a 23.5 GHz linear 16-element scanning phased array antenna based on thin ferroelectric film coupled microstripline phase shifters and microstrip patch radiators.

INTRODUCTION

A prototype scanning 16-element linear phased array using $Ba_{0.60}Sr_{0.40}TiO_3$ films on 0.3 mm thick MgO has been developed. The array is intended to be a steppingstone to collision avoidance radar suitable for automotive applications because of its potential to provide a much lower cost solution for certain Intelligent Vehicle Highway Systems. The phase shifters are based on a series of coupled microstriplines of length l and separation s patterned over pulsed laser deposited $Ba_{0.60}Sr_{0.40}TiO_3$ films nominally 400 nm thick. The maximum coupled voltage occurs when the coupled sections are a quarter wavelength long (i.e., $\beta l = 90^o$). Bias up to 400 V is applied to the sections via printed bias-tees consisting of a quarter-wave radial stub in series with a very high impedance quarter-wave microstrip. By concentrating the fields in the odd mode, the phase shift per unit length is maximized and by using the ferroelectric thin film form the effects of high loss tangent are minimized. Selecting the strip spacing s involves a compromise among: minimizing insertion loss, simplifying lithography, and minimizing the tuning voltage. Strip widths are chosen to approximate a 50 Ω characteristic impedance. These coupled microstrip devices rival the performance of their semiconductor counterparts at Ku- and K-band frequencies. Typical insertion loss for room temperature ferroelectric 360^o phase shifters at K-band is $\approx$5 dB [1-3].

PHASE SHIFTERS

The multilayer phase shifters have been analyzed using a computationally efficient variational method to calculate the even and odd mode capacitance [4,5]. If a quasi-TEM type of propagation is assumed the propagation constant an impedance can be completely determined from line capacitance. Since the cascaded coupled line circuit resembles a series of one-pole bandpass filters, as the dc bias increases, the dielectric constant of the BST film decreases, causing the passband to rise in frequency (and the *tan* δ of the BST to decrease). The impedance matrix of the cascaded network can be derived by well-known coupled line theory using the superposition of even and odd mode excitation. Then an equivalent S-parameter model can be extracted and used to predict the pass-band characteristics of the phase shifter.

The bandwidth compression from tuning is evident in fig. 1 which is data from an 8-section phase shifter on 0.3 mm MgO using a 400 nm $Ba_{0.60}Sr_{0.40}TiO_3$ laser ablated film. The roll-off at the upper end of the frequency range is attributed to bias-tee effects. The bias tees have a 25 μm wide, 1.83 mm long high impedance line connected to a radial stub with flare angle of 75° and radius 1.17 mm.

PHASE ARRAY DESIGN

The 23.5 GHz array consists of a monolithic 1:16 microstrip beam forming manifold constructed on 0.25 mm thick Duroid 6010, 16 ferroelectric phase shifters patterned on ≈1×0.75 cm MgO substrates, and a monolithic set of microstrip patch radiators patterned on 0.25 mm thick Duroid 5880. Inter-element spacing is 7.49 mm, which corresponds to about 0.57 free-space wavelengths. The layout is shown in fig. 2.

The original manifold, which had each successive branch of the divider networks separated by only 1.3 mm, experienced severe coupling problems resulting in considerable loss and asymmetry between ports. The distance was increased to 4 mm and resulted in a uniform insertion loss of about 13.0±0.25 dB. The patch array was originally fabricated on high dielectric constant material ($\varepsilon_r = 10.2$). However, when the resonant frequency of each patch was measured using a HP 8510C automatic network analyzer a large discrepancy was seen between each one. The variation was attributed to dielectric constant tolerances. Indeed substrate tolerances are known to cause serious errors in phased array performance [6]. To circumvent the problem a low dielectric constant homogenous material was selected. When the array was redesigned on 0.25 mm thick Duroid 5880, the variation in resonant frequency was much smaller, about 5 percent, and the bandwidth was adequate. Figure 3 depicts the measured frequency response. The patch dimensions are: L = 4.27 mm, W = 6.40 mm, and δ = 1.04 mm. The gap between the feed inset and patch was 0.38 mm. No particular attention was given to reducing sidelobe levels or reducing spurious radiation from the manifold or feed. The measured far-field radiation pattern at boresight is shown in fig. 4. The E-plane corresponds to the elevation direction and the H-plane corresponds to the azimuth direction. The array can scan past 45° before the appearance of a grating lobe.

An electronic module was designed and built to control the array. It consists of 16 independently addressable dc-to-dc converter channels. A model AOB 16/16 analog to digital converter interfaces the controller with a PC. Since the A/D could only source 5 mA per channel, an operational amplifier buffer (OPA547) was inserted between the A/D outputs and Pico Electronics model 12AV500 encapsulated dc-dc converters. A 1 W, 1 MΩ resistor is strapped across the transformers output to prevent a no-load condition. Since the dc input resistance of the phase shifters is >>1 MΩ, the applied voltage is essentially the programmed voltage. A 0.1 μF capacitor rated at 1 KV provides some filtering. Finally, an LED status indictor on each channel senses whether a thermal overload condition is present. The controller board is shown in fig. 5. It consumes about 25 mA per channel under normal conditions.

CONCLUSIONS

A linear K-band phased array has been demonstrated using novel coupled microstrip thin film ferroelectric phase shifters. The phase shifters capitalize on odd mode propagation to maximize phase tuning and minimize insertion loss. Despite a fairly common misconception that ferroelectric materials have too high a loss tangent for practical microwave applications, these devices can outperform their semiconductor counterparts by several dB. The phased array realized with these phase shifters holds promise to significantly reduce manufacturing costs of phase arrays because the phase shifters are lithographed using a simple two-step process. And the finest feature size is the strip spacing, about 10 μm, compared to perhaps a 0.5 μm gate for a MESFET phase shifter at the same frequency. To the best of our knowledge, this is the first demonstration of a K-band phased array based on ferroelectric films.

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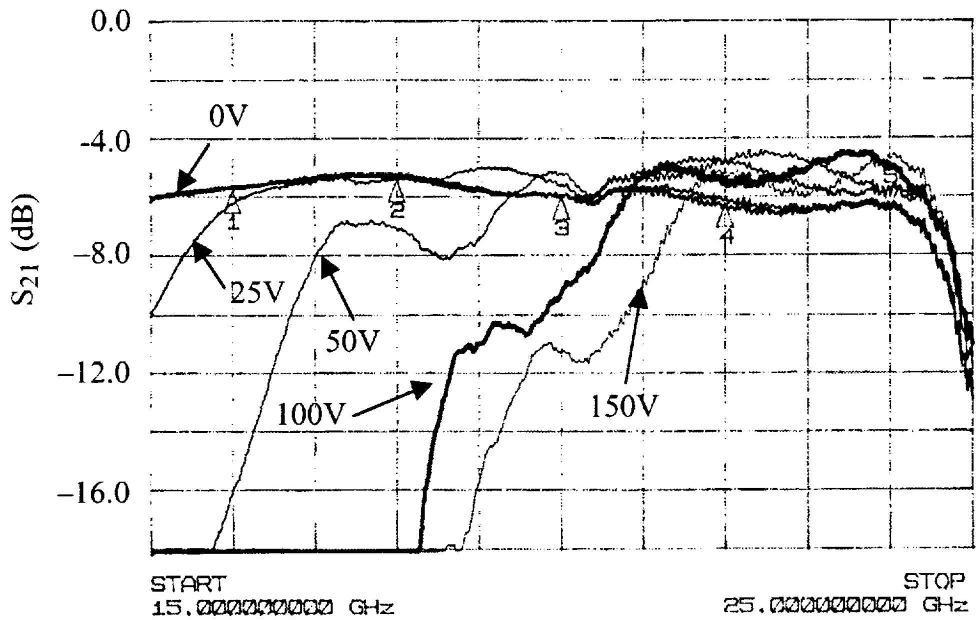

Figure 1.—Measured Insertion Loss (including SMA launchers) of an 8-element ≈50 Ω PLD coupled microstripline phase shifter at 290 K as a function of bias voltage. Substrate is 0.3 mm MgO with 400 nm $Ba_{0.60}Sr_{0.40}TiO_3$ film. l = 350 µm, s = 7.5 µm and w = 30 µm. Bandwidth compression from the filtering effect is evident. Marker 1, 2, 3, and 4 are at –5.75, –5.38, –6.00, and –6.49 dB, respectively.

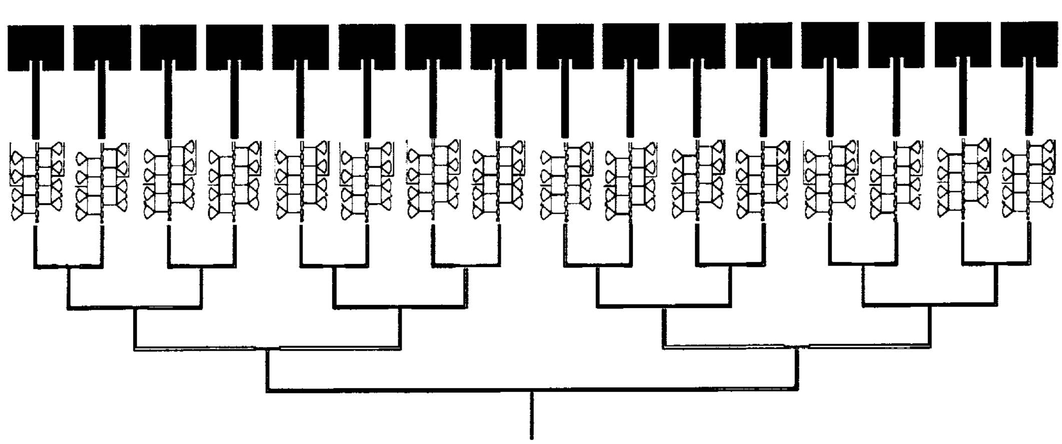

Figure 2.—Layout of the 16 element 23.675 GHz array. The array is 11.9 cm long.

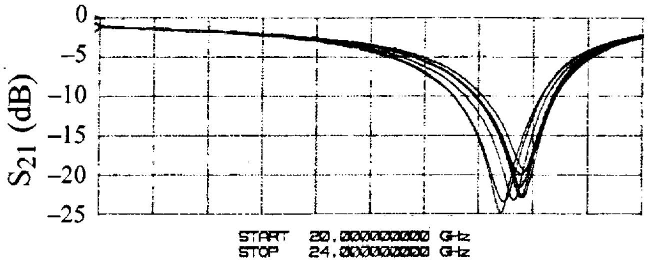

Figure 3.—Measured resonant frequency of patch radiators on 0.25 mm Duroid 5880 (εr = 2.2), 1 oz. Cu clad material.

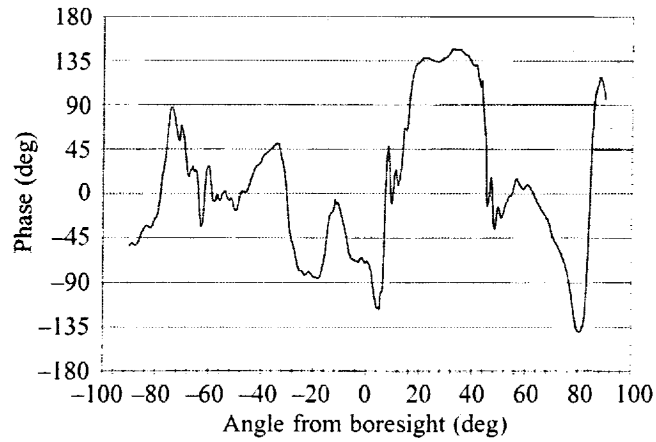

Figure 5.—Measured far-field H-Plane pattern corresponding to a 120 deg incremental phase shift.

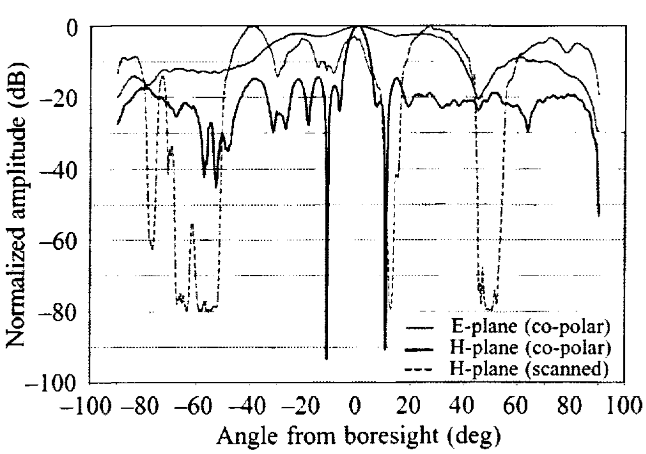

Figure 4.—Measured far-field E-Plane (elevation) and H-Plane (azimuth) pattern of the 16-element ferroelectric phased array at 23.675 GHz, 0 and 120 degree incremental phase shift.

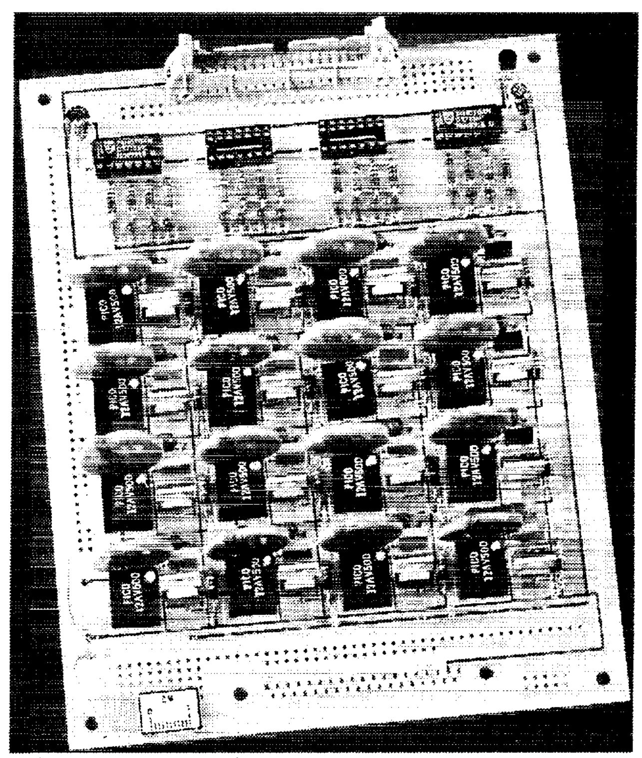

Figure 6.—High voltage controller board for the 16-element phased array. The board measures 19cm × 14.5 cm. The board accepts a 0-10 V signal from a 16 channel A/D converter and outputs a linear 0–400 V control signal.

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